

BioDOME

Multi-Mission Biological Sample-Return Vehicle



BioDOME

Biopan Deployment in Orbit for Microgravity Exposure



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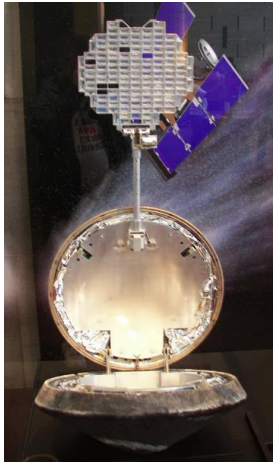
Georgia Institute of Technology, Atlanta, GA, 30332

Mission Goal and Review of Relevant Systems

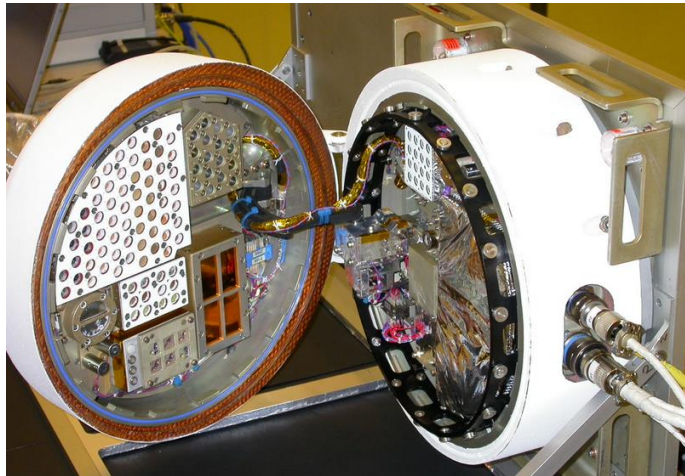
- **Goal:** Return of small biological samples from LEO
- **Mission Types:** ISS return and free flyer scenarios



RED-Data¹



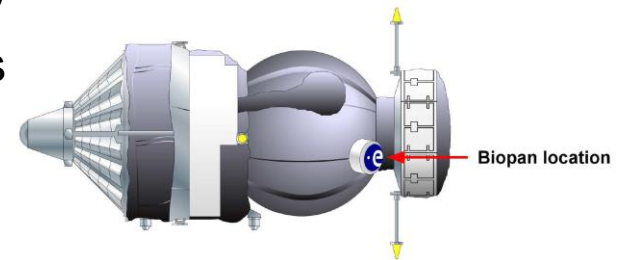
Stardust³



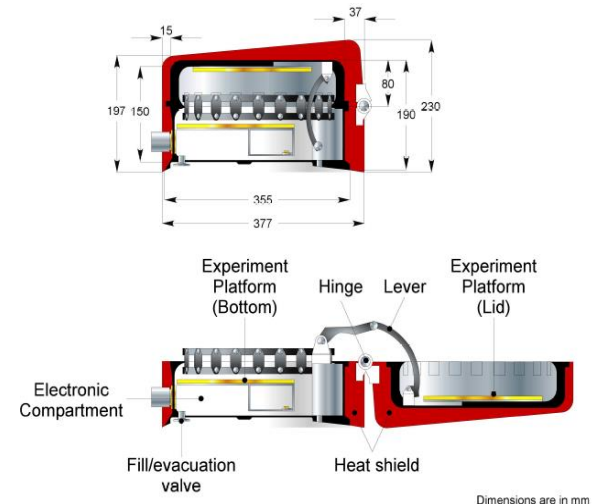
Biopan²

Biopan Design Advantages

- Volume efficient design for bio samples
- Self-contained environment when closed
- Exposure to space when opened

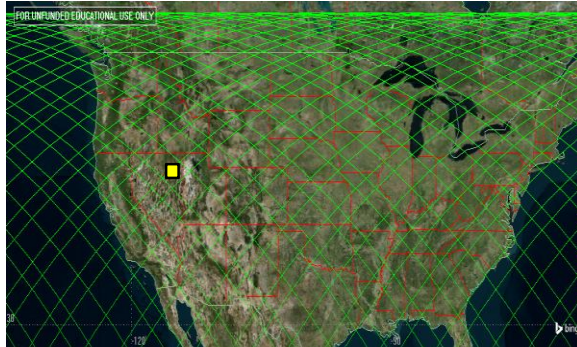


Foton Capsule with Biopan Location²



Biopan Cross-Section²

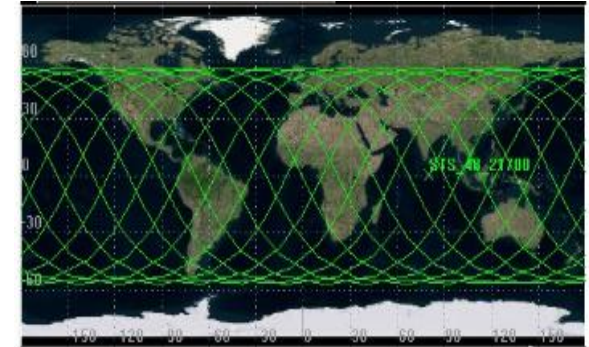
Mission Concepts: ISS Return and Free Flyer Options



One Week ISS Ground Track



Kibo ISS Module and JEM-EF⁴



STS 48 Ground Track at $i = 57^\circ$

ISS Return Only

Advantages

- Enters through Kibo cargo hatch
- Easy access for astronauts via Kibo direct entry

Constraints

- Carrying propellant onboard is a safety hazard
- Orbit inclination limited to 51.6°
- Kibo hatch diameter limited to 0.6 m

BioDOME Docked Outside ISS

Advantages

- ISS return and free flyer vehicles can be identical
- Can attach to JEM Exposed Facility (JEM-EF) port
- Access for astronauts is possible using the JEM Remote Manipulator System (JEMRMS)

Constraints

- Max diameter of 0.97 m for Pegasus payload fairing
- Increased docking complexity

Free Flyer Return Only

Advantages

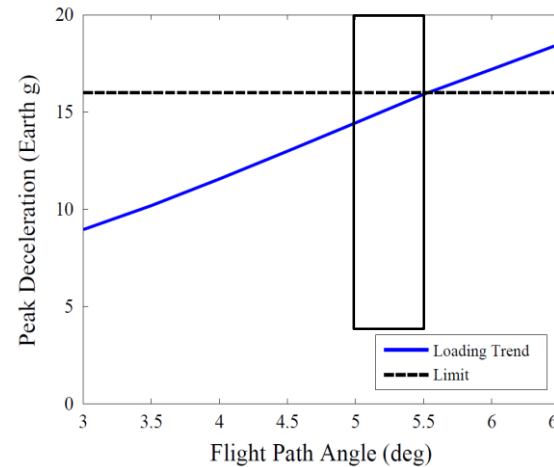
- Flexible orbit inclination
- Larger diameter vehicle possible

Constraints

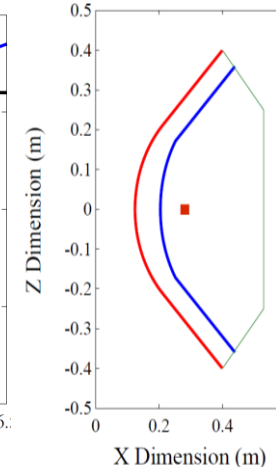
- Inclination must be greater than 42° for UTTR landing site
- Service module required for stand-alone orbit mission

Heatshield Sizing: Trade Study Selection of Trajectory and Aeroshell Size

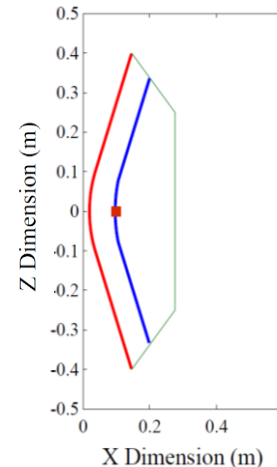
- Flight path angle window between 5° - 5.5° chosen to reduce TPS thickness and maintain low peak deceleration
- Ballistic entry chosen to reduce risk and complexity
- 45° sphere cone chosen for expected stability benefits during ballistic entry
- Aeroshell shape and size selection performed simultaneously



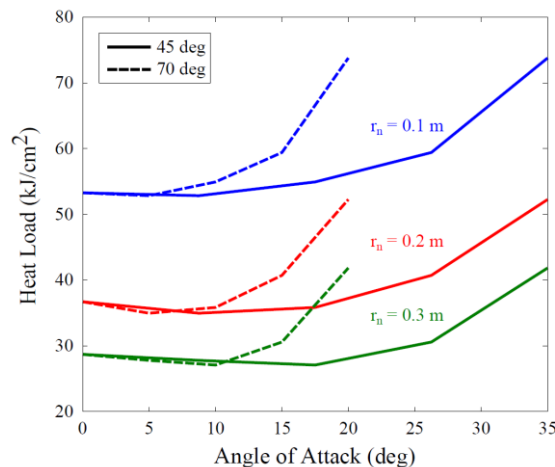
Peak Deceleration vs. FPA



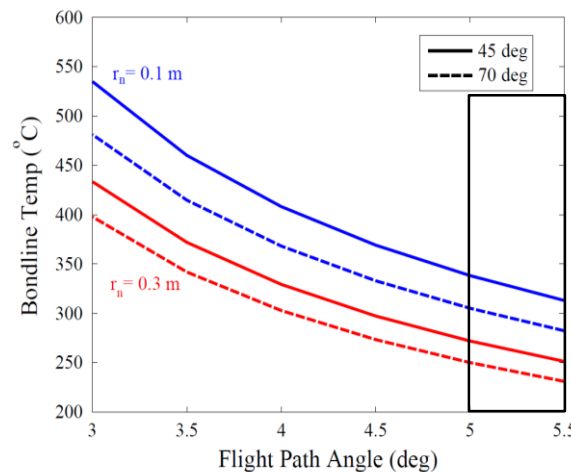
45° Sphere Cone



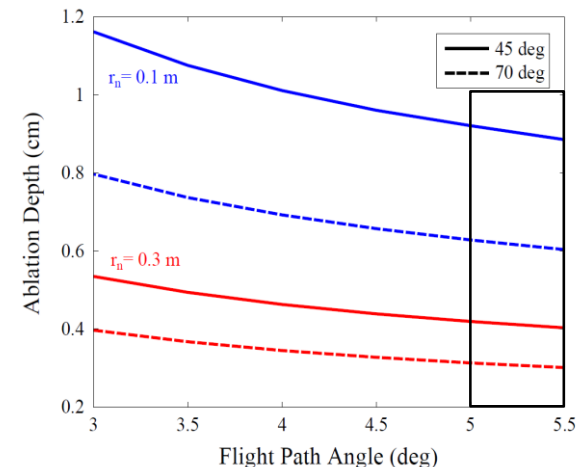
70° Sphere Cone



Heat Load vs. AoA



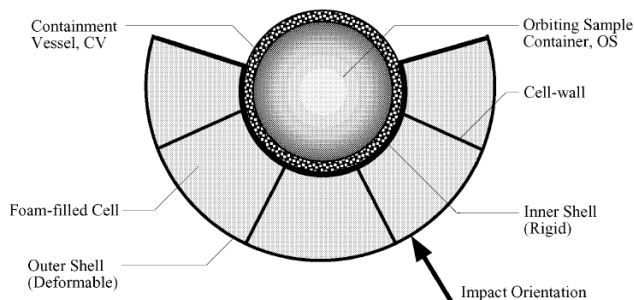
Bondline Temperature vs. FPA



Ablation Depth vs. FPA

Passive Landing System: Trade Study Between Crushable System Design and Landing Velocity

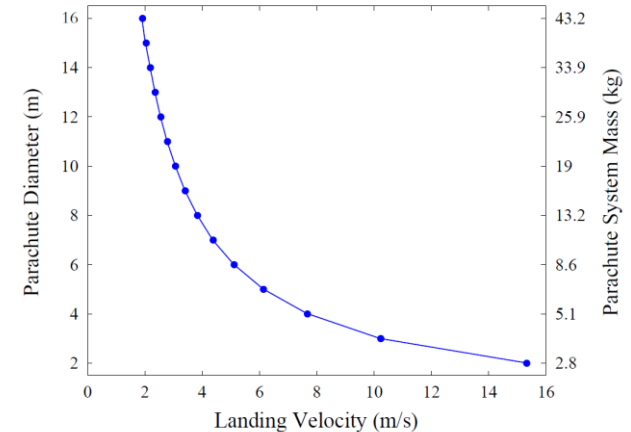
- Sized parachute and crushable passive landing system simultaneously to find target touchdown velocity at UTTR
- Chose to land carbon foam hemisphere at 4 m/s to balance overall passive landing system mass and thickness



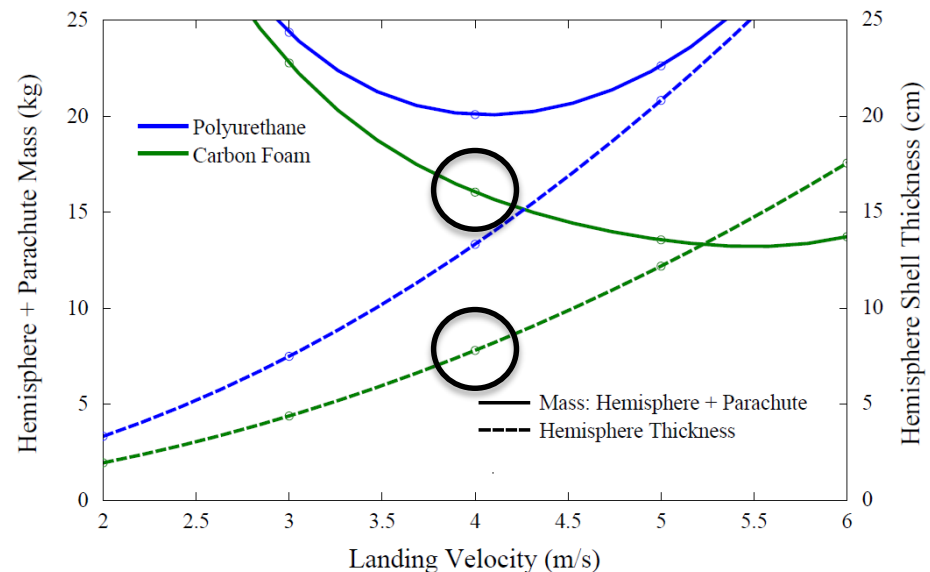
Hemispherical Crushable Concept⁷



Ringsail Parachute⁶



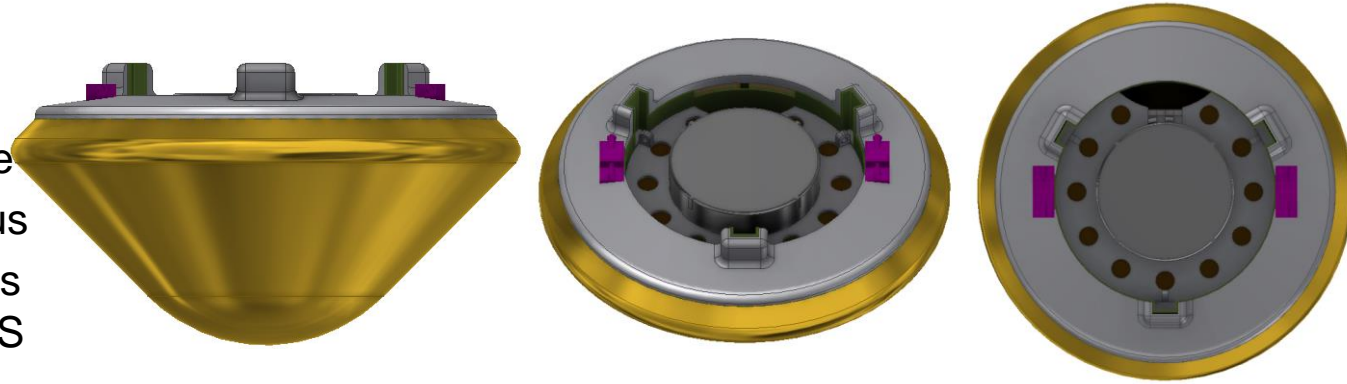
Parachute Sizing Trade Study



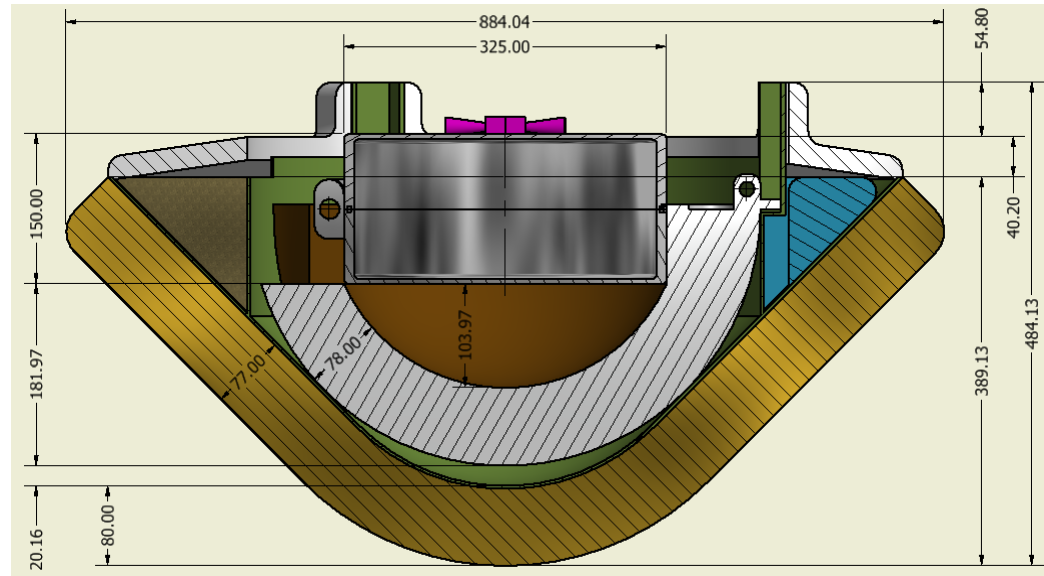
Crushable/Parachute System Trade Study

BioDOME Final Design

- Diameter: 88 cm
- Height: 50 cm
- Shape: 45° Sphere cone
- Launch Vehicle: Pegasus
- Mission: Biopan exposes samples to space for ISS return and free flyer return scenarios
- Entry: De-orbit kick motor and RCS spin stabilization to achieve initial entry conditions
- Descent: Ballistic trajectory to parachute deploy and primary vehicle ejection
- Landing: Parachute descent to crushable hemisphere passive landing



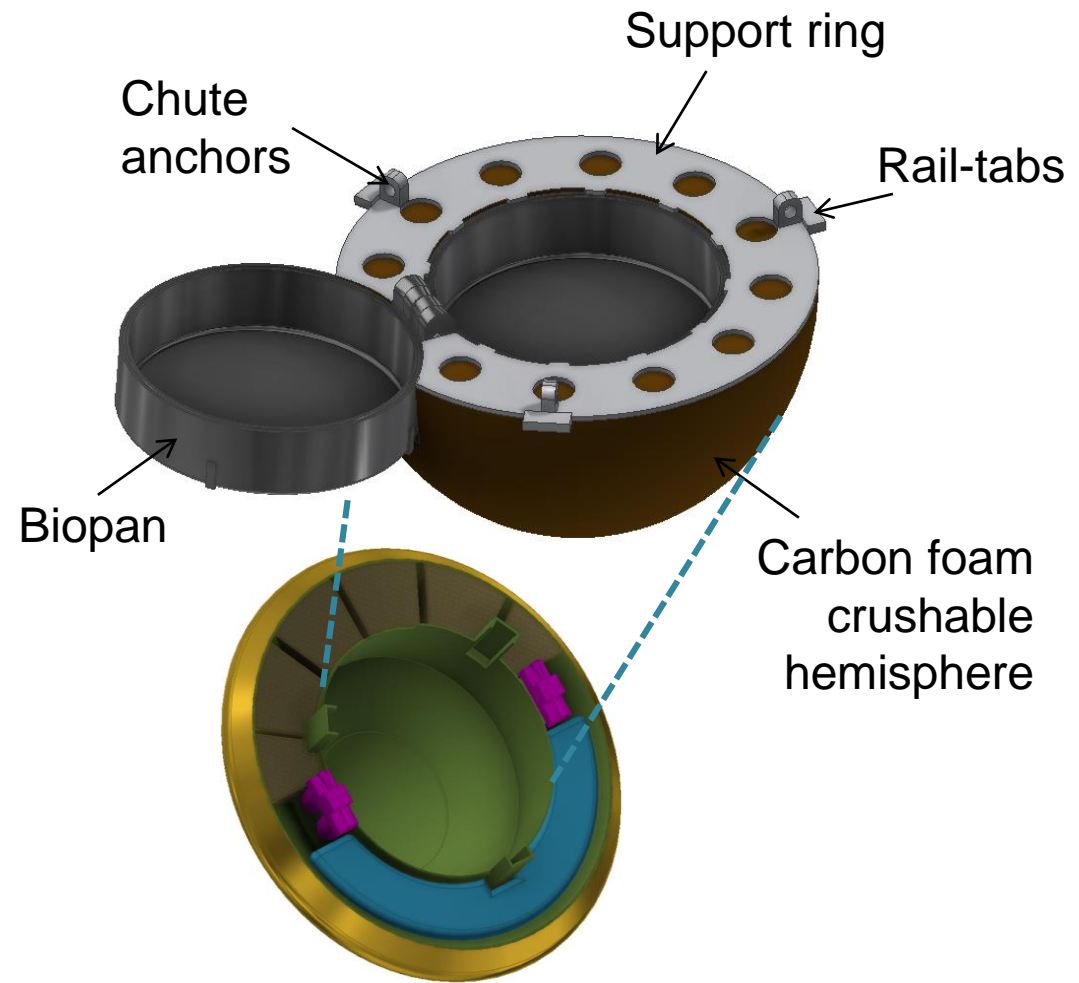
BioDOME Full Vehicle CAD Model



BioDOME CAD Model Cross Section

BioDOME Final Design

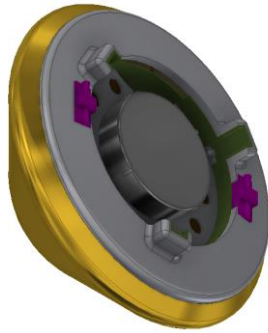
- Biopan raised on rails for robotic arm capture during ISS retrieval/return scenario
- Biopan raised on rails to expose biological samples to space for free flyer return scenario



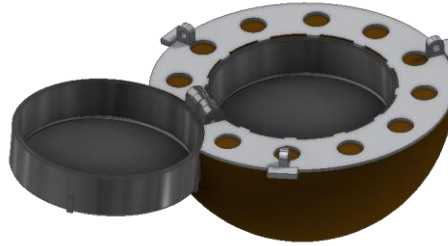
**Biopan System Raised and Exposed to Space
for Free Flyer Return Scenario**

**Biopan System Retrieval from BioDOME
for ISS Return Scenario**

BioDOME Final Design



Full BioDOME Vehicle



Post Ejection Vehicle



**Post Ejection
Descent System⁶**

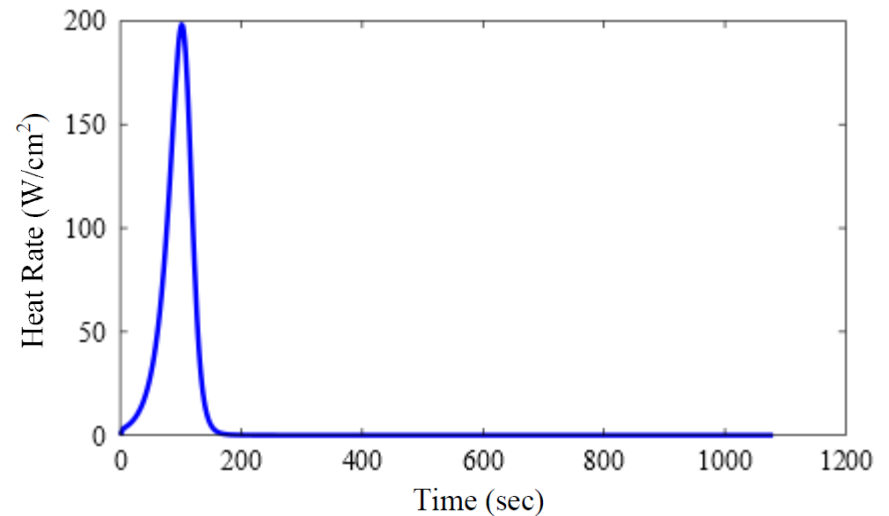
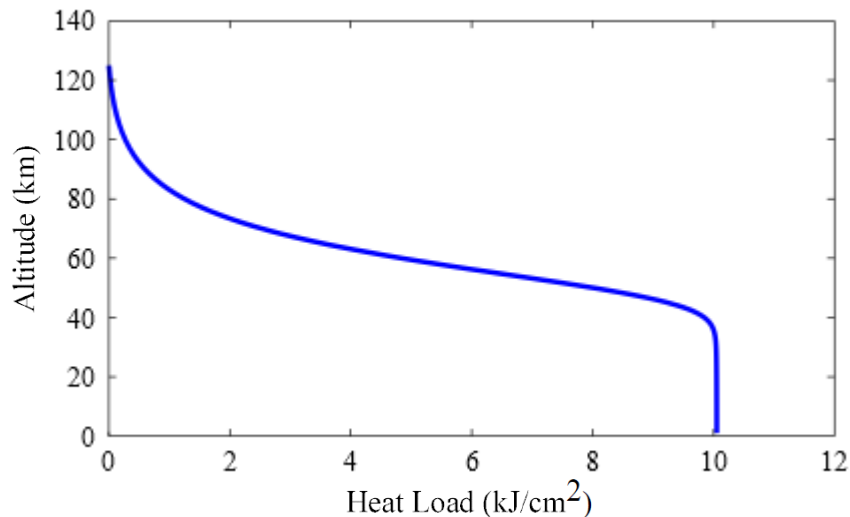
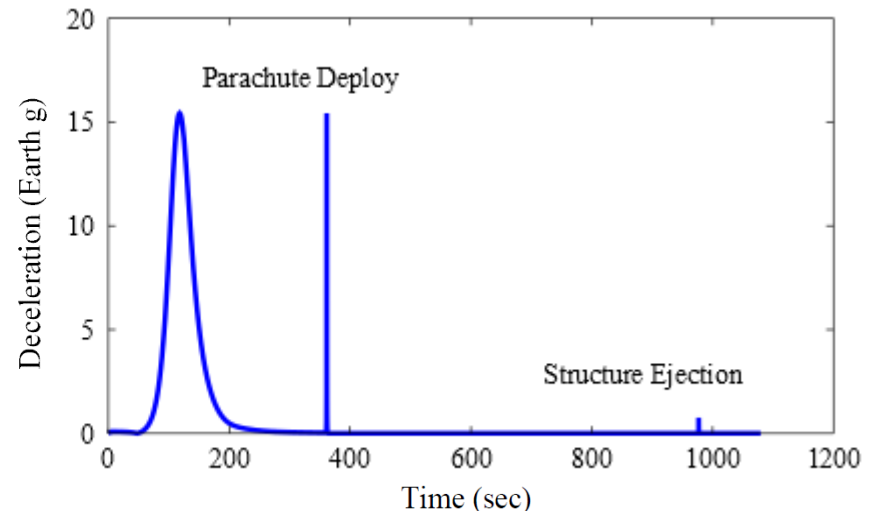
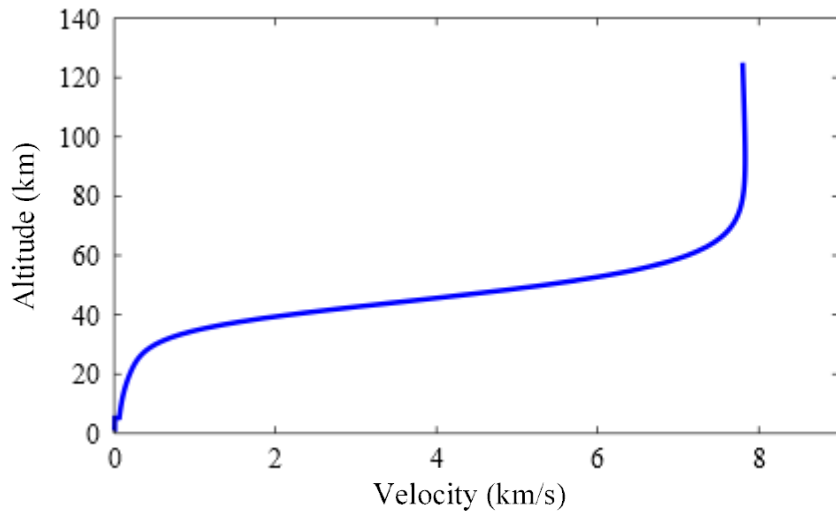
BioDOME Vehicle Mass Breakdown

Payload (Biopan)	15.0	kg
Crush Hemisphere	2.0	kg
Parachute	13.2	kg
RCS	12.0	kg
Structures	15.0	kg
TPS	15.0	kg
Aftbody	2.0	kg
Total Mass	74.2	kg

Post Ejection Mass Breakdown

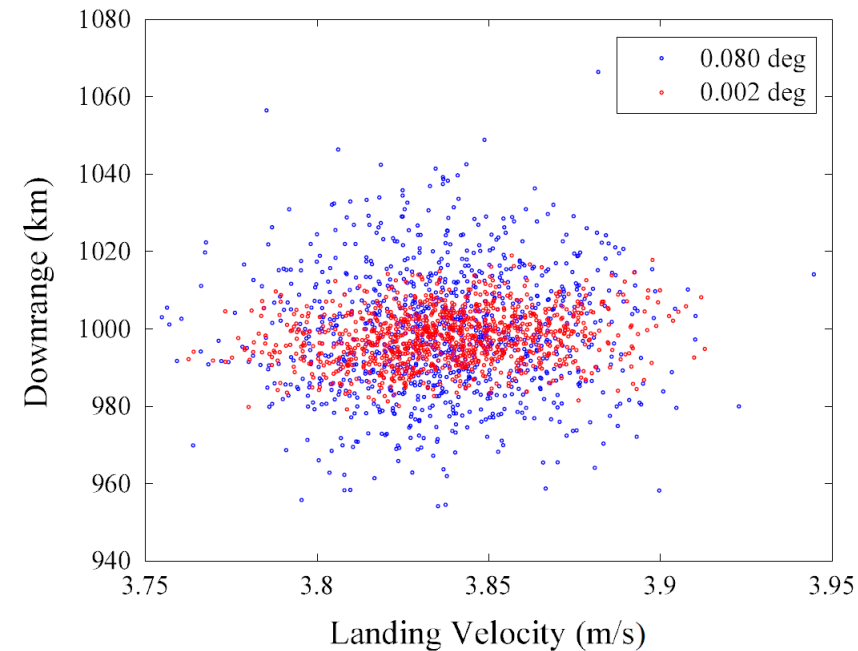
Payload (Biopan)	15.0	kg
Crush Hemisphere	2.0	kg
Parachute	13.2	kg
RCS	EJECTED	kg
Structures	5.4	kg
TPS	EJECTED	kg
Aftbody	EJECTED	kg
Total Mass	35.6	kg

BioDOME Nominal Trajectory and Mission Profiles

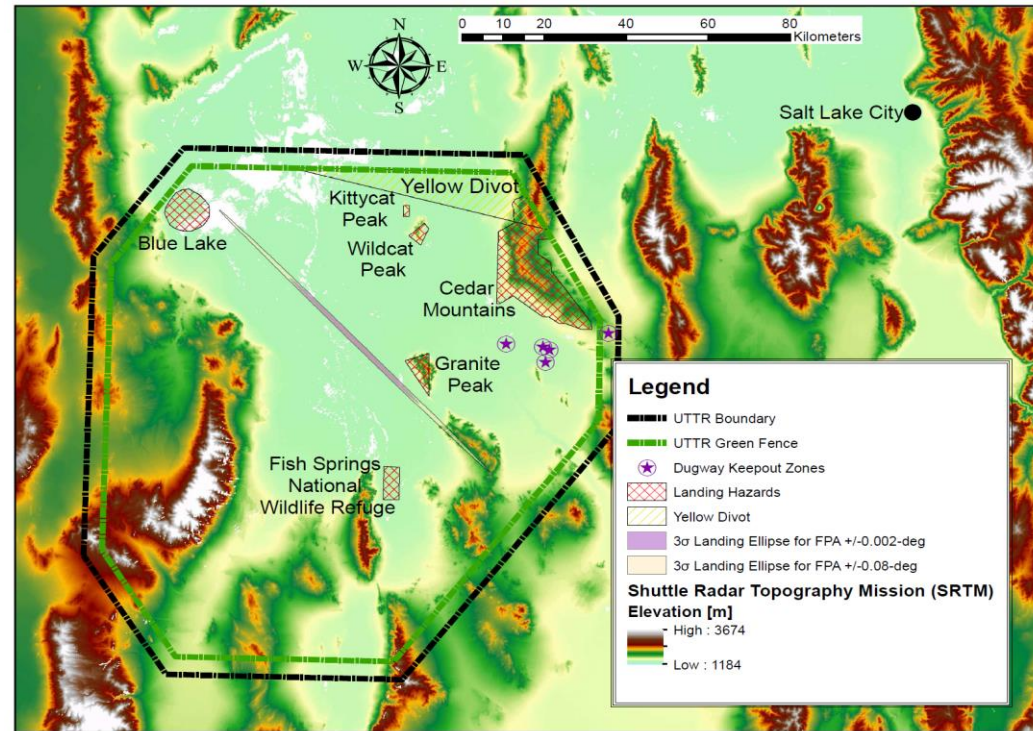


Nominal Trajectory and Mission Profiles

Monte Carlo: Dispersion Analysis and Landing Site



Monte Carlo Landing Velocity Dispersion



Mapped on Utah Test and Training Range (UTTR)^{3,8}

Size of Landing Ellipses

Large Landing Ellipse: 95.5 km x 1.36 km for $FPA = 5^\circ \pm 0.080^\circ$

Small Landing Ellipse: 45.5 km x 1.29 km for $FPA = 5^\circ \pm 0.002^\circ$

BioDOME Conceptual Design Study Summary

Goal: Return of small biological samples from LEO

Mission Types: ISS return and free flyer return scenarios

Conclusions

- BioDOME adds sample return flexibility for biological experimentation for ISS return, free flyer return, and future mission scenarios
- Identical vehicle chosen for both mission types using readily available concepts and materials from previous missions
- Conceptual EDL trade studies show promise for a feasible biological sample return from LEO with flexible mission architectures

Future Work

- Perform aerodynamic stability analysis and modify design accordingly to ensure stable entry
- Analyze aft body heating to select and size appropriate aft body TPS
- Perform trade studies to optimize primary vehicle ejection sequence

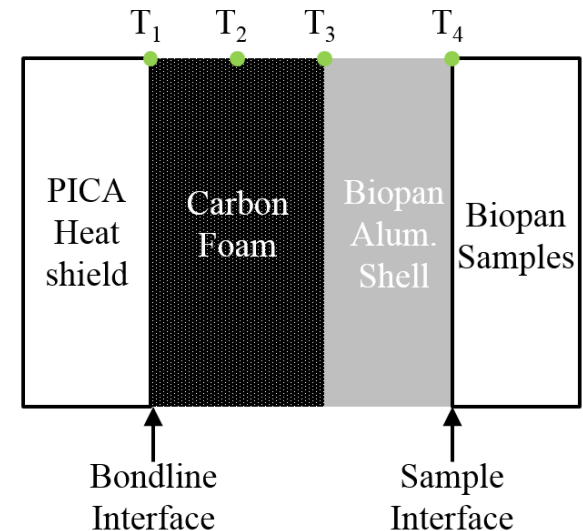
References

- [1] Terminal Velocity Aerospace LLC, “Delivering a Suite of ReEntry Devices (REDs) to Enhance Safety and Promote Space Utilization,” <http://www.tvaero.com/products.shtml>, cited October 2014.
- [2] Noetzel, R. T. et al., “BIOPAN Experiment LICHENS on the Foton M2 Mission Pre-Flight Verification Tests of the Rhizocarpon Geographicum-Granite Ecosystem,” *Advances in Space Research*, Vol. 40, 2007, pp. 1665 – 1671.
- [3] Tooley, J., Lyons, D., Desai, P., and Wawrzyniak, G., “Stardust Entry: Landing and Population Hazards in Mission Planning and Operations,” *AIAA/AAS Astrodynamics Specialist Conference and Exhibit*, No. AIAA-2006-6412, 2006.
- [4] Space REF, “ISS Spacecraft: Progress,” <http://www.spaceref.com/iss/spacecraft/progress.html>, cited October 2014.
- [5] Ewing, E. G., Bixby, H. W., and Knacke, T. W. "Recovery System Design Guide." AFFDL-TR-78-151, 1978.
- [6] http://www.tafsm.org/PROJ/AS/Orion08A/Main_Full-C.jpg
- [7] Kellas, S., “Design, Fabrication and Testing of a Crushable Energy Absorber for a Passive Earth Entry Vehicle,” Contractor Report NASA/CR-2002-211425., NASA Technical Reports Server, Fairfax, Virginia, April 2002.
- [8] USGS (2004), “Shuttle Radar Topography Mission, 3 Arc Second scene,” Filled finished 2.0, Global Land Cover Facility, University of Maryland, College Park, Maryland, February 2000.

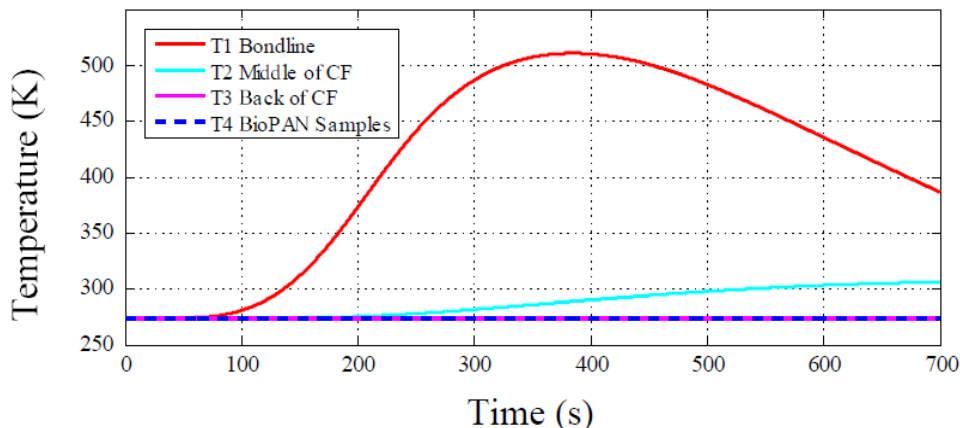
Backup Slides

Thermal: Conceptual Heat Transfer Analysis

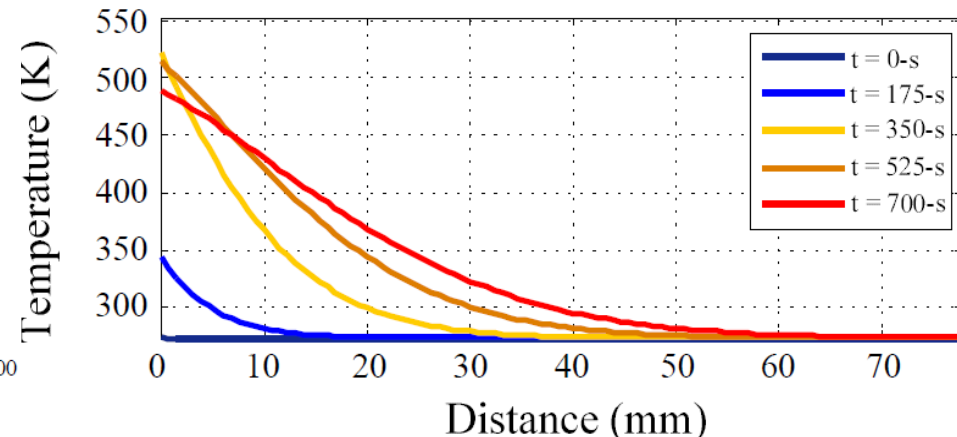
- Conceptual 1D heat transfer analysis performed at stagnation point from bondline to Biopan interior
- Finite difference method was applied to calculate temperature as a function of time and depth
- 7.7 cm thick PICA heatshield keeps sample interface temperature well under 250°C (523 K) limit for RTV bonding agent



Conceptual 1D Thermal Analysis Diagram



Temp vs. Time at Depth Using 4 FD Nodes



Temp vs. Depth Using Many FD Nodes

Monte Carlo: Dispersion Analysis and Landing Velocity

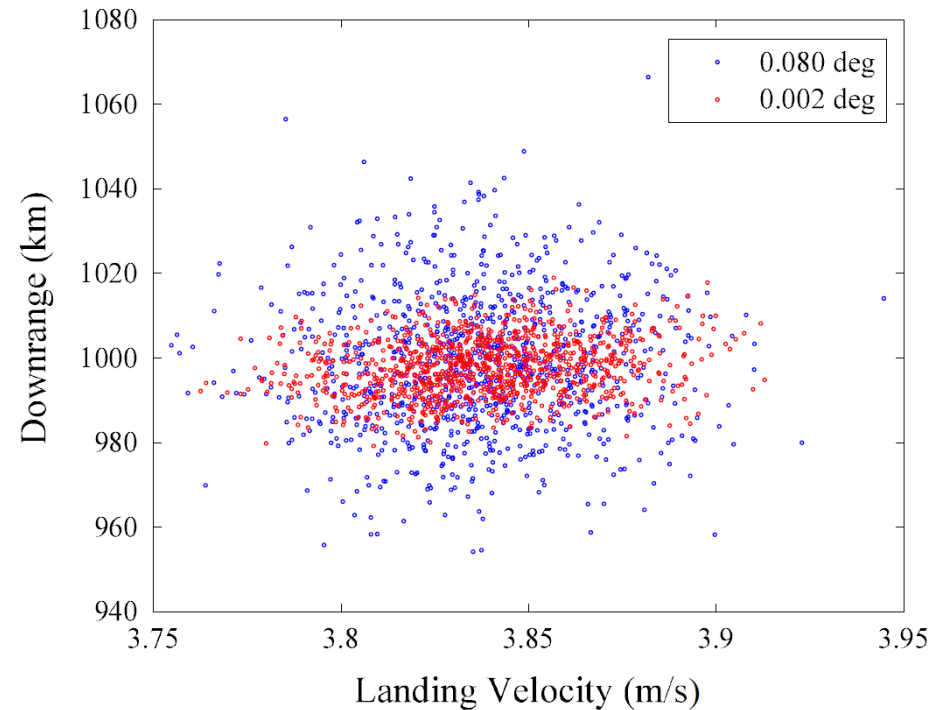
- Performed Monte Carlo analysis examining resulting landing velocities from flight path angle perturbations
- Identified that the majority of velocities fall below the designed landing velocity of 4 m/s

Monte Carlo Input Variables

Input Variable	Nominal	Variation	Distribution
Entry Vel. [m/s]	7800	± 25	Normal
Entry FPA [deg]	-5.0	± 0.080	Normal
Entry Alt. [km]	125	± 0.050	Normal
Ref. ρ [kg/m ³]	1.225	Earth GRAM	Uniform
Scale Height [m]	7200	0	Normal
Crosswind [m/s]	0	Earth GRAM	Normal

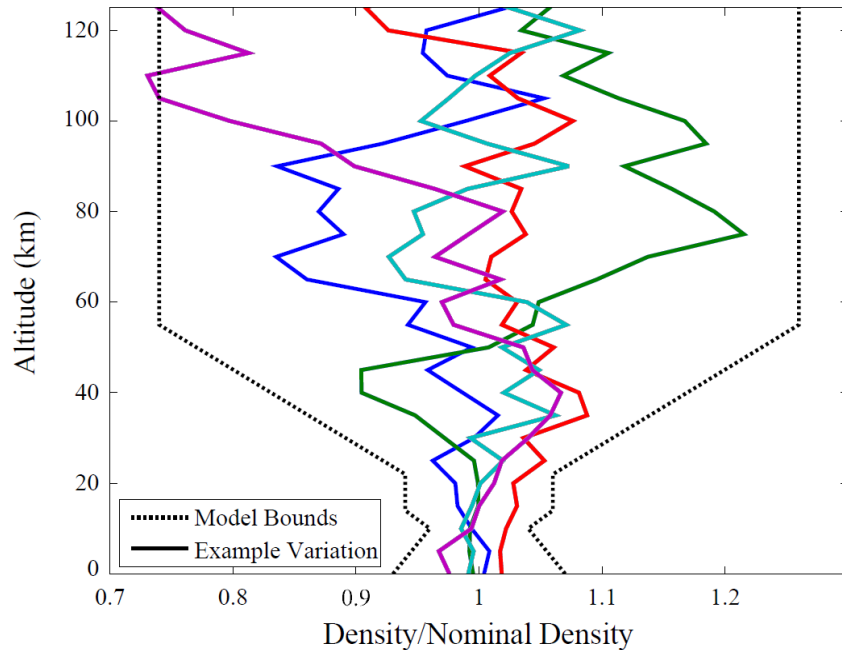
Monte Carlo Results Summary

Event	μ	σ	Range
Time to Land [s]	1092	21.35	1030 - 1157
Deceleration [Earth g]	16.09	0.545	15.4 - 18.4
Downrange [km]	998	15.9	954 - 1066
Heat Flux [kJ/cm ²]	195	5.02	179 - 211
Heat Load [kJ]	9.89	0.162	9.4 - 10.5
Crossrange [km]	4.35	0.22	3.64 - 5.17
Touchdown Velocity [m/s]	3.83	0.027	3.75 - 3.94

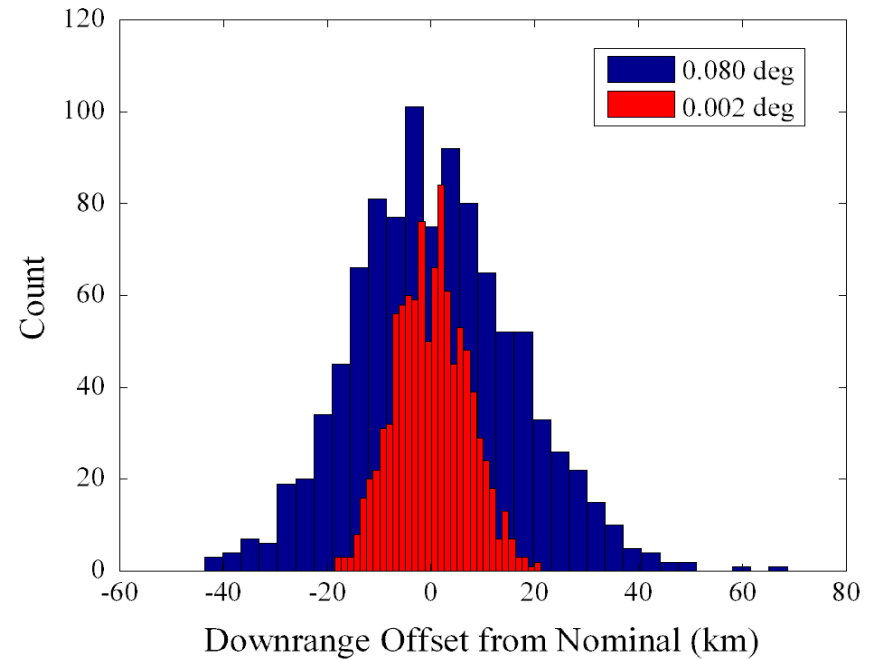


Monte Carlo Landing Velocity Dispersion

Monte Carlo: Implementation Description



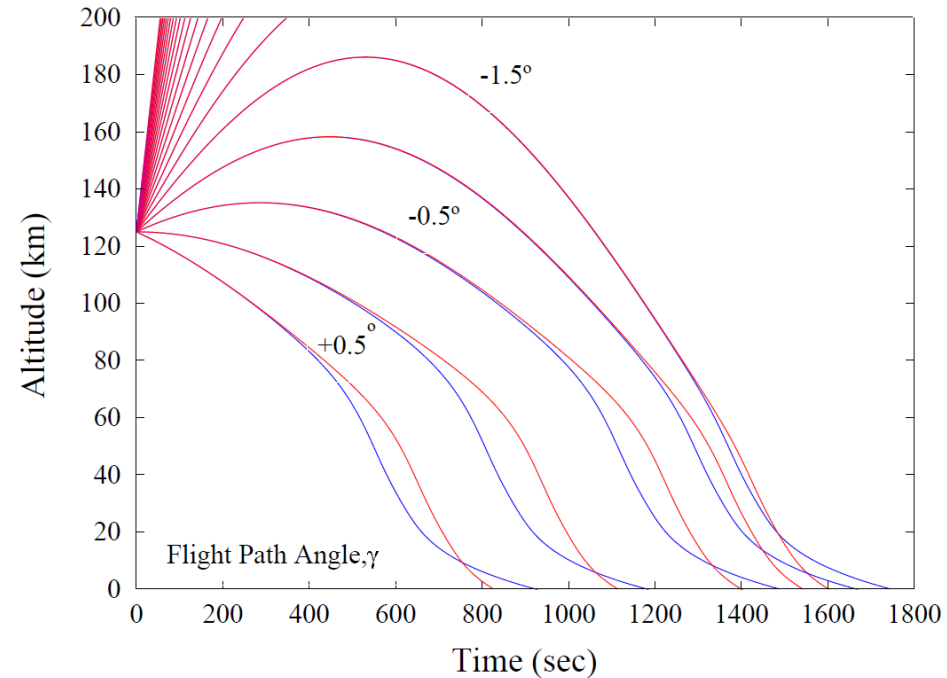
Earth GRAM Implementation



Histogram of Downrange Monte Carlo Simulations (1000 Runs)

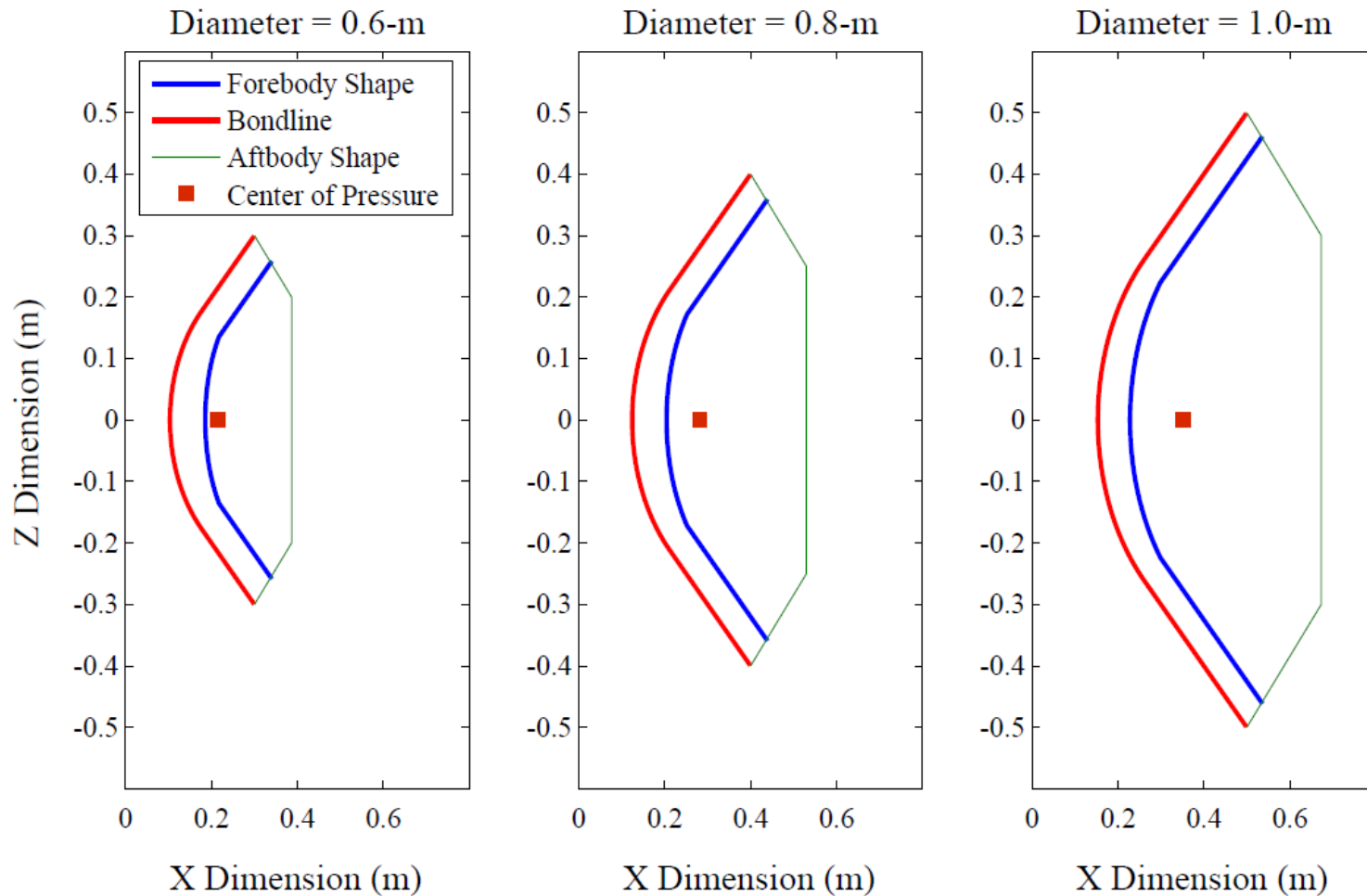
Trajectory: Trade Study Identifying Entry Corridor (FPA)

- Seek to limit altitude gain
- Regardless of **parachute** deploy behavior or **ballistic coefficient**, initial FPA drives altitude
- FPA of 0.5° necessary to enter atmosphere
- **Heating environment** and **load limitations** set *upper bound* on FPA



Minimum Flight Path Angle Definition

Trajectory: Vehicle Shape and CG Location



Vehicle Sizing Trade Study

BioDOME Concept of Operations

~700-km

ISS Orbit (~413 – 423 km)

Inclination = 51.6°

Free-Flyer Orbit (~280 km)

Inclination > 42°

Kick Stage Deorbit Burn

Thermosphere

45° Sphere-cone Ballistic Reentry
@ 120 km

~80-km

Mesosphere

Peak Heat Rate =
198.5 W/cm² @ 56.4
km

Mesopause

~50-km

Stratosphere

Peak Deceleration =
15.45 g's @ 47.2 km

Stratopause

~12-km

Troposphere

Tropopause

Descent:

1. Subsonic Ringsail Parachute Deploy - Mach .2, 3000-4000m
2. Jettison Primary Structure at 1.4 km

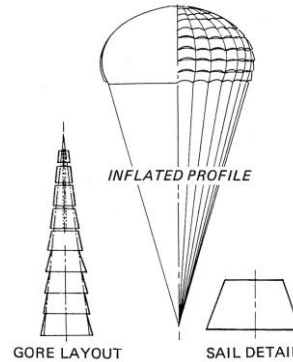
Landing @ 1 km:

Total Heat load = 10063 J
+/- .002° FPA yields 45.5 x 1.29 km ellipse
Sustained Impact Load < 16 g's

Questions?

Aerodynamic Decelerators: Parachute Sizing Trade Study

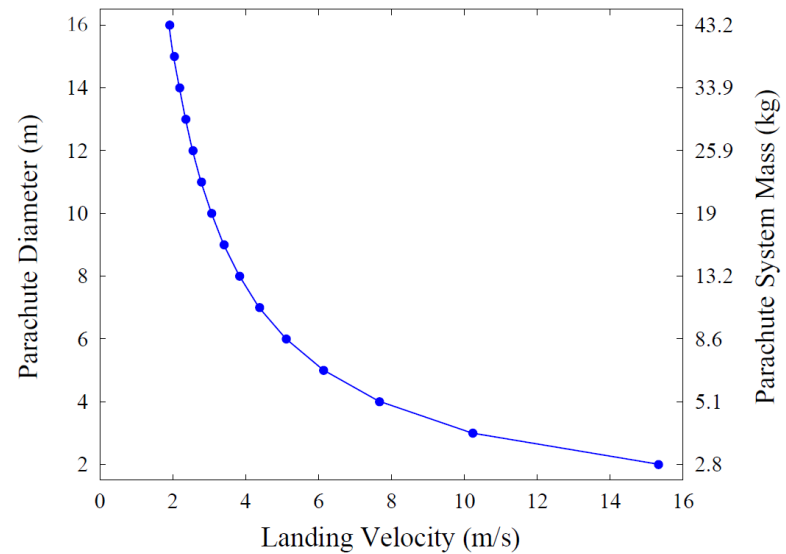
- Ringsail parachute benefits include high drag coefficient and low mass
- Single parachute will be used for subsonic deployment
- Sized simultaneously with passive landing system to provide optimal touchdown velocity in the UTTR
- Final parachute design:
 - Ringsail parachute selected with diameter of 8 m
 - Total parachute system mass of 13.2 kg
 - Hydraulic vacuum packed into 40 cm³ with density of 0.64 g/cm³



Ringsail Parachute Diagram⁵



Fully Inflated Ringsail Parachute⁶



**Parachute Mass and Diameter
vs. Desired Landing Velocity**

Simulation: Numerical Integration

- Basic Premise: Propagate forward dynamics throughout time as you would in Excel.
- Except, with Matlab we can be more clever about propagating forward, how we handle termination, and more precise in event triggering.
- The 'Classic' Vision of numerical integration is First Order Forward Euler
- Limitations of Forward Euler
 - Fixed Timestep results in long simulation time without consideration of system dynamics
 - Maybe we can have a larger timestep, maybe we need a smaller one
- Thus, adapt timestep

Simulation: Numerical Integration Adaptive Timestep

- Estimate error at each step, set timestep to bound error
- Example, estimate $\underline{x}(t+\Delta t)$ at (1) step of $2\Delta t$ or (2) step of Δt
- Error due to step size is then: $\varepsilon = \underline{x}_2 - \underline{x}_1$
 - Reduce Δt if $\varepsilon > \varepsilon_{\max}$
 - Increase Δt if $\varepsilon < \varepsilon_{\min}$
- Start with an upper bound of timestep, and then iterate downward (smaller Δt) until the error is within bound
- Repeat this at each timestep to find the optimal timestep

Simulation: Timestep Adaptation

- Adaptive timestep results in significantly reduced simulation duration
- FO Forward Euler
 - $\Delta t = 0.01$, Time to Run = 15.9 seconds
 - $\Delta t = 0.1$, Time to Run = 0.661 seconds
 - ~5% difference between 0.01 and 0.1 seconds on heat rate
- 6-Step Adaptive (RFK56)
 - $\text{Elim} = 0.000001$, Time to Run = 0.461 seconds
 - $\text{Elim} = 0.0000001$, Time to Run = 0.596 seconds
 - $\text{Elim} = 0.00000001$, Time to Run = 0.812 seconds
- General cases above, there are a lot of finer points and variations
- **Takeaway: Decrease sim time, don't assume as much about model**

Simulation: General Structure

- *Handles* structure
 - Passes in and out of each function (like a GUI)
 - State, State Rate, time, timestep, etc.
- Plug and play integration routine, derivative, print, terminate, etc.
 - Sutton-Graves equation provided relation for heat rate vs. time
 - Adaptive versus fixed timestep easily changed
- Basic Outline
 - Determine next state (integration routine)
 - Increment iteration count
 - Advance time from previous timestep
 - Record the data from previous
- **Interestingly, this is the same structure the EDL team at JPL uses (except theirs is in C)**